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Modeling forest landscape change in the Missouri Ozarks under alternative management practices

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Abstract

We used a spatially explicit landscape model, LANDIS, to simulate the effects of five management alternatives on a 3216 ha forest landscape in southeast Missouri, USA. We compared management alternatives among two intensities of even-aged management with clearcutting, uneven-aged management with group selection harvest, a mixture of even- and uneven-aged management, and no harvesting. Anticipated disturbances by windthrow and wildfire were included in the 100-year simulations across the landscape. The uneven-aged, even-aged long rotation, and mixed harvest regimes were similar to one another in total area in each forest size class, timber volume produced and volume of wood on the forest floor. However, they varied greatly in quantity of edge habitat and in the extent of the mature forest habitat free from edge effects. The intensive even-aged harvest regime and the no-harvest regime produced the greatest volume of timber and the greatest volume of down wood, respectively. This model provides a quantitative flamework to simultaneously explore multiple factors that affect landscape-scale management decisions.

Keywords: Simulation; Volume yield; Patch size; Edge; Landscape pattern; Timber harvest; Clearcutting; Group selection; LANDIS

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1. Introduction

Forests are the source of many things that people value: wood products, wildlife, water, recreation, scenery, and solitude. Management of forest ecosystems for these and other values requires an understanding of how forests change over time in response to succession, natural disturbances, and management practices such as timber harvest. Inherent in virtually all forest management plans is the underlying requirement of sustainability — that forests will be managed in a manner so that their future capacity to produce products, services, and amenities will not be diminished. However, many alternative sustainable management programs can be selected for a given forest. Some emphasize forest products, others emphasize dispersed recreation opportunities, and still others emphasize biodiversity.

Every forest management activity, even the decision to do nothing, sets in motion patterns of forest vegetation change that persist for decades or even centuries. Sustainable forest management demands that managers learn as much as possible about the long term effects of management alternatives. This requires understanding how management activities and natural disturbances affect landscapes over time and space. Forest vegetation will change due to harvest and natural disturbances, and subsequent forest growth and succession will alter the size structure and species composition across a landscape. Ultimately, forest managers should be concerned with the short- and long-term effects of prescribed management activities and natural disturbances on the products and amenities that people value.

Methods to regulate and optimize the flow of forest products from a given area while still ensuring long-term product sustainability have been studied at length. However, optimizing forest values such as species diversity, forest aesthetics, or wildlife habitat quality is more difficult, particularly when the values are difficult to quantify numerically. The problem is further compounded by differences in relevant spatial scales for different forest resources. Management and inventory of forest products is usually implemented in individual forest stands, typically 2–50 ha in extent. In contrast, many wildlife species have habitats that span hundreds or thousands of hectares. For example, there are more than 180 species of neotropical migrant birds that nest in forests of the Midwestern United States each spring and summer (Probst and Thompson, 1996). These avian species have different habitat requirements and assessing habitat quality requires a landscape perspective that accounts for the spatial arrangement of forest vegetation, open lands, and edge habitats (Thompson et al., 1996). Habitat assessment for many other wildlife species is equally complicated and requires an examination of conditions at a scale larger than the individual stand.

Joint assessment of timber and other forest resources requires mechanisms to integrate information about anticipated ecosystem disturbance processes (e.g. harvest, wind and fire) and to evaluate their impact on a range of different forest values that are often measured at different spatial and/or temporal scales. LANDIS is one landscape simulation model that has been used to simulate long-term changes in forest age structure and species composition in the Lake States (He et al., 1996; Mladenoff et al., 1996 He and Mladenoff, 1999). LANDIS can be applied to mapped forest landscapes from a few hundred ha to over 100 000 ha in extent. Simulations of future forest conditions are spatially explicit and maps of simulated landscape conditions can be used in conjunction with a geographical information system (GIS) to analyze forest vegetation patterns at large spatial scales. Simulation of changes in forest vegetation across a mapped forest landscape provides a critical link that allows the assessment of a wide array of associated forest characteristics over time (e.g. timber, wildlife and aesthetic qualities).

We use the LANDIS model to simulate the effects of five management regimes on a forested landscape in the Missouri Ozarks. We briefly describe the capabilities and limitations of the LANDIS model. We also examine the assumptions and resource yield relationships that are required to simulate change in the temporal and spatial distribution of forest age classes, size classes and timber volume in the Missouri Ozarks. We then apply LANDIS to simulate long-term change in vegetation on a 3261 ha forest landscape in the Missouri Ozarks. We compare the long-term impacts of five different management regimes on the simulated pattern of forest vegetation size and age classes. Comparisons include patch size and length of forest edge in addition to maps showing spatial arrangement of forest size/age classes. We also estimate volume of timber harvest, volume of residual standing timber, and volume of wood on the forest floor over a century of simulated change.

2. Methods

2.1. The LANDIS model

LANDIS is a spatially-explicit forest landscape model that simulates forest change over time with (or without) the disturbance processes of fire, wind and harvest and their interactions (He et al., 1996; Mladenoff et al., 1996; Mladenoff and He, 1999; Gustafson et al., 2000). LANDIS was designed to simulate forest change in 10-year increments over large landscapes and to track the spatial arrangement of the resulting forest conditions. LANDIS was originally developed for species and forest conditions in the Lake States, but recently it has been adapted for Missouri Ozark forests by recalibrating the species reproduction probabilities for species and ecological land types found in the region (Shifley et al., 2000).

Internally, LANDIS represents the forest landscape as a matrix of sites or cells, each corresponding to one square raster unit or pixel on a map. We used sites that were 30×30 m (0.09 ha) in size, but sites can be scaled as necessary for different simulation objectives. Forest vegetation on each site is represented as the presence/absence of trees by species at 10-year age class intervals. Information about tree species and age classes can be used to estimate species dominance for a given site. Data from multiple sites can be combined to estimate age structure or forest vegetation composition for a group of sites (e.g. for a stand). An additional map layer required by LANDIS defines ecological land types or eco-regions within which environmental conditions that affect species establishment and historical fire distributions are expected to be similar. The size, frequency, and intensity of simulated fire events can also be varied by land types. Fire damage to individual sites varies with the fire tolerance of the species present on a site and with the relative fuel loads (a function of time since last fire and any recent wind damage) (He and Mladenoff, 1999). We based simulated fire size and frequency on wildfire patterns recorded over the last three decades by the Mark Twain National Forest and the Missouri Department of Conservation (Westin, 1992). Data on wind disturbance in the Missouri Ozarks came from 96 km of line transects in the Missouri Ozarks sampled by Alan Rebertus in 1995–96 (personal communication).

Other map layers define forest stands and groups of stands called management areas. These are used to simulate timber harvest in LANDIS (Gustafson et al., 2000). Timber harvest practices can differ for each management area. Simulated harvests within a given management area can be restricted to stand boundaries or may be allowed to spread to adjacent stands until they cover a specified area. All common forest harvest practices can be simulated.

Simulated disturbance events kill or harvest species in one or more age cohorts. Recruitment of new trees is based on spatially explicit seed dispersal and seedling establishment defined by reproduction probabilities that are specific to an ecological land type. Reproduction probabilities consider species' longevity, shade tolerance, seed dispersal distances, and sprouting probability. In the absence of disturbance for a given simulation cycle, the vegetation present on a site moves to the next older (10-year) age cohort, and shade tolerant species may be recruited into the youngest age class.

At any given decade during a simulation, the species and age cohorts can be examined on individual sites, vegetation characteristics for individual sites can be aggregated and summarized (e.g. by stand, by species or by age class), and the spatial distribution of vegetation characteristics can be analyzed. Ultimately, the condition and spatial arrangement of vegetation conditions on sites across the forest landscape can be used to estimate levels of forest products, amenities, or habitat characteristics of interest. LANDIS is not suitable for site specific planning; rather it is a tool to get a landscape-scale view of simulated future forest conditions (Mladenoff and He, 1999)

2.2. Study area

The forest landscape we examined in this study is a 3216 ha portion of the Mark Twain National Forest in northern Oregon county, southeast Missouri (Fig. 1). Missouri Highway 19 splits the landscape in two sections, and this linear feature is conspicuous by the absence of forest cover. This forested region was heavily logged between 1890 and 1920. The second-growth forests are a mixture of white oak (*Quercus alba*), post oak (*Q. stelatta*), black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), hickory (*Carya spp.*), and shortleaf pine (*Pinus echinata*). Slopes typically range from 0 to 33 percent; half the sites had a slopes ≤ 11 percent. Site quality is relatively low (site index ≈ 19 m at age 50) with the better sites found on the northeast slopes and in stream bottoms. Ecological land types, stand maps, and vegetation characteristics for each stand were provided by the Mark Twain National Forest.

2.3. Initial conditions

We assigned initial vegetation conditions for each site on the landscape based on the age class and forest type recorded during the most recent forest inventory. We grouped Miller's (1981) ecological landtypes (recorded for each site) into seven broader ecological landtypes for use with LANDIS: south and west slopes, north and east slopes, ridge tops or upland flats, upland waterways, floodplains or low terraces, side slopes on limestone, or glades. We populated each 30×30 m space on the initial digital landscape with one of four species groups (white oak group, black oak group, shortleaf pine group, or maple group). We based initial species abundance by landtype on proportions observed in data collected for the Missouri Ozark Forest Ecosystem Project (Brookshire and Shifley, 1997).

2.4. Harvest regimes

We evaluated five harvest regimes (Table 1). They varied in the type of harvest, the area harvested each decade, and the distribution of harvest sites. The even-aged intensive harvest regime clearcut $\approx 10\%$ of the area each decade (on average a 100-year rotation) with the oldest stands harvested first. The even-aged long rotation harvest regime reduced the clearcut area to 5% per decade (on average a 200-year rotation) and extended the minimum rotation age to 80 years. The uneven-aged management regime harvested 5% of the area per decade with group openings averaging 0.2 ha in size. The mixed harvest regime included a combination of clearcutting and group selection was on 5% of the area each decade. In the mixed

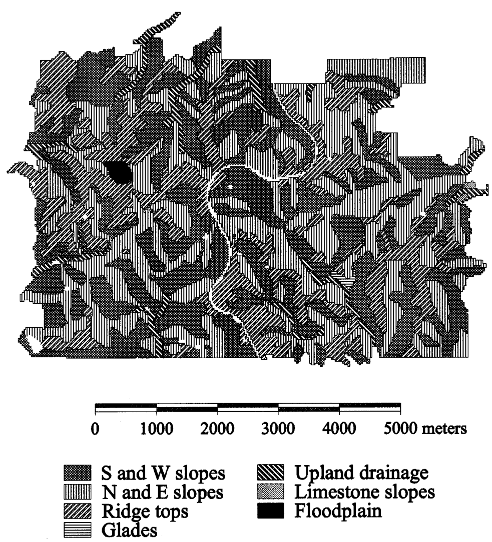

Fig. 1. Ecological landscape types across the 3261-ha study region on the Mark Twain National Forest. Simulated vegetation response to disturbance differs by landtype.

Table 1
Summary of the five harvest and natural disturbance regimes compared using LANDIS

Criteria	Harvest regime				
	Even-aged intensive	Even-aged long rotation	Uneven-aged	Mixed	No harvest
Area harvested per decade (%)	10	5	5	5	0
Method of harvest	Clearcut	Clearcut	Group selection[a]	Clearcut and group selection[b]	Not applicable
Minimum harvest age	50	80	50	50	Not applicable
Stand selection criteria	Oldest first	Oldest first	Oldest first	Oldest first	Not applicable
Mean interval between repeat fire damage (years)	300	300	300	300	300
Mean interval between repeat wind damage (years)	800	800	800	800	800

[a] Group selection openings had a mean size 0.2 ha.
[b] Clearcut on NE slopes; group selection on SW slopes, ridges, and floodplains.

regime, clearcutting was applied to forests on north and east slopes; group selection harvests were applied to forests on south and west slopes, ridge tops, and floodplains (Table 1). Other land units were not harvested. For all simulations we set 300 years as the mean period between repeat wildfires at a given site. We set 800 years as the mean period between repeat occurrences of intensive wind damage at a given site. The simulated wind and fire events were only those of sufficient size and intensity to kill overstory trees in an area ≥ 0.09 ha. Blowdowns of individual trees were not included in the simulation.

2.5. Characterization of landscape conditions

The LANDIS model reports the 10-year age class for each site on the landscape at each decade of simulation. Simulations included up to 17 different age classes (age 0–170). To improve clarity of figures and tables and to aid interpretation of results, we summarized age class data into the following forest size classes: seedling (age 0–9), sapling (age 10–29), pole (age 30–59), and sawlog (age ≥ 60). Reported values for the old-growth size class correspond to that portion of the sawlog size class, that is ≥ 100 years old.

We used a variety of techniques to summarize the forest landscape conditions for each harvest regime at each decade of the simulation. We computed age and size class frequencies with commercially available GIS software. We computed patch size and edge statistics using FRAGSTATS (McGarigal and Marks, 1995). We defined patch boundaries and edges by size classes (seedling, pole, sapling, and sawlog). We defined sawlog core area as the total area in the sawlog size class that was ≥ 100m from an edge with any other size class. We estimated volume yields by age class for each site based on average yields by age class observed during the 1989 inventory of the Mark Twain National Forest (Kingsley and Law, 1991; Hansen et al., 1992). We estimated volume of down wood by age class as a function of time since last disturbance based on equations and data from Spetich et al. (1999), Jenkins and Parker (1997) (Table 2).

3. Results

3.1. Vegetation age structure

The forest size class distributions that result from the five harvest regimes produce notably different spatial patterns (Fig. 2). The even-aged intensive and long-rotation harvest regimes resulted in relatively large patches of forest in a variety of size classes. The mixed and uneven-aged harvest regimes show the small patch structure associated with numerous 0. 1–0.3 ha group selection regeneration openings. The no harvest management alternative produced large expanses of mature forest (predominantly > 100 years old) with small patches of younger forest that result from fire and wind disturbance.

Table 2
Estimated volume of timber and coarse wood debris by age class on the Mark Twain National Forest[a]

Age class	Growing stock (Bd.ft/ha)	Growing stock (m^3/ha)	Down wood (m^3/ha)
1–10	207	9	79
11–20	1350	32	64
21–30	2984	50	52
31–40	4585	61	42
41–50	6174	67	34
51–60	7323	70	29
61–70	8122	72	26
71–80	8630	72	25
81–90	8927	72	26
91–100	9087	73	29
101–110	9168	73	33
111–120	9206	73	39
121–130	9223	73	46
131–140	9230	73	55
141–150	9232	73	65
151–160	9233	73	75
161–170	9234	73	87
171–180	9234	73	100
181–190	9234	73	113
>190	9234	73	127
All ages	7486	65	57

[a] Timber volumes are the smoothed average for 331 plots measured on the Mark Twain National Forest as part of the 1989 inventory (Kingsley and Law, 1991). Down wood volumes were estimated from Spetich et al. (1999) and Jenkins and Parker (1997).

The number of sites by size class is similar for the even-aged long rotation harvest regime, the uneven-aged harvest regime, and the mixed harvest regime (Fig. 3). Each of these three regimes harvest $\approx 5\%$ of the forest area each decade, but the distribution of that harvest across the landscape results in conspicuously different spatial arrangements on the landscape (Fig. 2). The no harvest regime and the even-aged intensive harvest regimes are characterized by the presence (95% of area) and absence (1% of area) of old-growth forest, respectively. The even-aged intensive harvest regime maintains relatively constant proportions among size classes after 60 years of simulation, but for the other harvest regimes the proportion of area by size class changes continuously over the 100 years of simulation (Fig. 3).

3.2. Landscape patterns

The forest size class patterns on the landscape can be characterized by the patch sizes (Table 3) and length of edge (Table 4). These statistics change at every decade in the simulation, but the values for the final landscapes after 100 years of simulation highlight the relatively small size of the sawlog patches associated with the two even-aged harvest regimes and the relatively small patch sizes for seedling, sapling and pole size classes that result from the other three regimes. The sawlog core area (sawlog area >100 m from any other adjacent size class) is greatest for the no harvest regime. The sawlog core area is only half as large under the even-aged long rotation harvest regime, and it drops another 50% to 332 ha for the

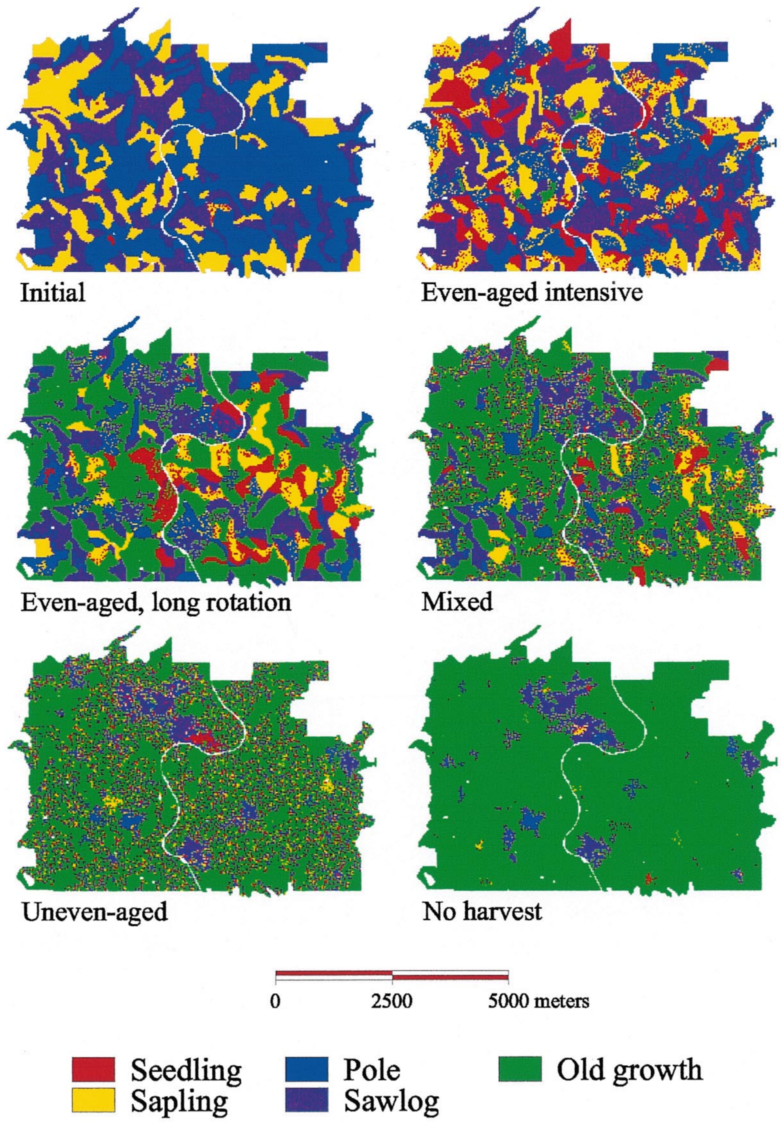

Fig. 2. Spatial pattern of initial forest size classes and patterns that result following 100 years of simulation for each of the five harvest regimes. Associated landscape statistics are found in Tables 3 and 4. size classes were summarized from age for each site: seedling (age 0–9), sapling (age 10–29), pole (age 30–59), sawlog (age 60–99), old growth (age >100).

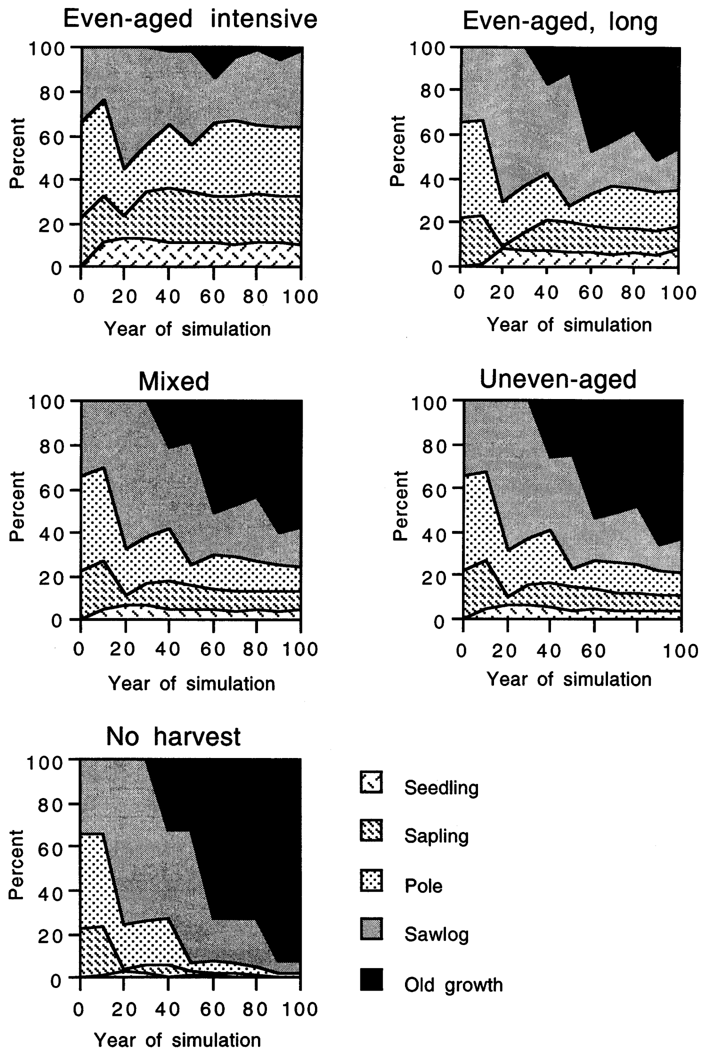

Fig. 3. Change in proportion of the forest size classes over time for five harvest regimes: even-aged intensive, even-aged long rotation, mixed, uneven-aged and no harvest. See Fig. 2 and Table 1 for additional details about harvest regimes and spatial arrangement of size classes across the landscape. Size classes were summarized from age for each site: seedling (age 0–9), sapling (age 10–29), pole (age 30–59), sawlog (age 60–99), old growth (age > 100).

mixed harvest regime. The uneven-aged harvest regimes, by virtue of many large and widely dispersed harvest patches, results in the smallest sawlog core area.

The uneven-aged harvest regime produced the greatest length of edge between size classes (Table 4). As expected, the no harvest management regime produced the least edge. The total length of edge for each of the four size classes was the most evenly balanced for the intensive even-aged harvest regime.

Table 3
Mean patch size (ha) by harvest regime and forest size class for the study area at the end of 100 years of simulation

Harvest regime	Seedling	Sapling	Pole	Sawlog	Core area[a]
Even-aged intensive	1.2	2.2	2.3	13.7	275
Even-aged long rotation	1.6	1.8	1.6	63.7	663
Mixed	0.3	0.3	0.3	103.9	332
Uneven-aged	0.2	0.2	0.2	103.2	179
No harvest	0.2	0.3	0.7	389.8	1340

[a] Core area is the total area of forest in the sawlog size class that is at least 100 m from any smaller size class.

Table 4
Length of edge (km) between size classes for the study area at the end of 100 years of simulation

Harvest regime and size class	Total edge	Length of edge with size class		
		Sapling	Pole	Sawlog
Even-aged intensive				
Seedling	334	173	43	118
Sapling	556		184	200
Pole	492			266
Sawlog	584			
Even-aged long rotation				
Seedling	207	82	15	109
Sapling	279		76	121
Pole	288			197
Sawlog	427			
Mixed				
Seedling	282	55	22	204
Sapling	422		61	306
Pole	406			322
Sawlog	833			
Uneven-aged				
Seedling	349	38	30	281
Sapling	521		53	430
Pole	489			406
Sawlog	1117			
No harvest				
Seedling	9	2	0	7
Sapling	17		0	16
Pole	47			47
Sawlog	70			

Table 6
Estimated volume (thousand m^3) of down wood by decade and harvest regime[a]

Year of simulation	Even-aged intensive	Even-aged long rotation	Mixed	Uneven-aged	No harvest
0	125	125	125	125	125
10	126	109	116	115	109
20	131	111	114	113	102
30	136	115	115	114	101
40	138	118	116	116	101
50	140	122	119	120	107
60	141	127	126	128	119
70	139	132	134	138	135
80	138	140	145	150	155
90	138	148	157	164	180
100	137	158	170	180	209
Mean	135	128	131	133	131

[a] Values are totals for the 3261 ha study area at the end of each decade.

3.3. Harvest and residual volumes

The estimated area harvested and volume removed was nearly constant by decade for the even-aged intensive, uneven-aged, and mixed harvest regimes (Table 5). For the even-aged long rotation harvest regime, no stands were harvested during the first decade because during that period no stands on the forest landscape met the minimum age requirement of 80 years (Table 1). For each of the subsequent decades the harvest for the even-aged long rotation harvest regime was ≈ 165 ha and 1.5 million board feet. Area and volume harvested under the even-aged intensive regime was more than double the amounts under the other harvest regimes. The remaining harvest regimes in order of decreasing area and volume harvested are even-aged long rotation, mixed, uneven-aged and no harvest. The combined cumulative harvest plus residual standing volume at the end of the simulation period followed the same order (Table 5). The estimated volume of standing (residual) timber at the end of the 100-year simulation period varied inversely with the total harvest volume and ranged from 18 to 24 million board feet per ha or 186–226 thousand m^3. Mean volume of down woody debris was similar for all harvest regimes, but values differed substantially by decade (Table 6). After moving through a period with relatively low down wood volumes in decades 2–4, the no-harvest management regime eventually produced the greatest volume of down wood.

3.4. Fire and wind disturbance

In the harvested landscapes, the extent of fire and wind disturbances was less than one-third the extent of area disturbed by harvest. Wind disturbance was

Table 5
Estimated harvest volume and residual standing volume for live trees by decade for five harvest regimes[a]

Year of simulation	Even-aged intensive		Even-aged long rotation		Mixed		Uneven-aged		No harvest	
	Harvest	Residual	Harvest	Residual	Harvest	Residual	Harvest	Residual	Harvest	Residual
	Million board feet									
0	0.0	18.7	0.0	18.7	0.0	18.7	0.0	18.7	0.0	18.7
10	2.7	19.2	0.0	22.0	1.1	20.8	0.8	21.1	0.0	22.0
20	2.8	18.9	1.4	22.7	1.0	22.0	0.9	22.3	0.0	24.1
30	2.9	18.2	1.5	22.8	1.0	22.7	0.9	23.0	0.0	25.5
40	2.8	18.1	1.5	22.9	1.1	23.4	0.9	23.7	0.0	27.0
50	3.0	17.9	1.5	23.2	1.1	24.1	0.9	24.5	0.0	27.9
60	3.0	17.8	1.5	23.2	1.1	24.4	0.9	24.8	0.0	28.5
70	2.9	17.9	1.5	23.5	1.1	24.8	0.9	25.2	0.0	29.0
80	2.9	17.9	1.5	23.5	1.1	25.0	0.9	25.5	0.0	29.4
90	3.0	17.8	1.6	23.6	1.1	25.2	0.9	25.8	0.0	29.6
100	3.0	17.9	1.6	23.3	1.1	25.3	0.9	25.9	0.0	29.8
Mean per decade	2.6	18.2	1.2	22.7	1.0	23.3	0.8	23.7	0.0	26.5
Total harvest	28.9		13.6		10.8		8.9		0.0	
Cumulative harvest plus residual at age 100		46.8		36.9		36.0		34.8		29.8
Year of simulation	*Thousand m^3*									
0	0	198	0	198	0	198	0	198	0	198
10	24	194	0	215	10	206	8	207	0	215
20	24	187	12	210	9	207	8	209	0	221
30	24	182	12	206	9	207	8	209	0	223
40	23	183	12	206	9	210	8	211	0	229
50	24	183	12	207	9	213	8	214	0	231
60	24	183	12	207	9	214	8	215	0	232
70	24	185	12	209	9	215	8	217	0	234
80	24	184	12	209	9	215	8	218	0	235
90	24	184	12	210	9	216	8	219	0	236
100	24	184	12	206	9	216	8	219	0	236
Mean per decade	22	186	10	208	8	211	7	212	0.0	226
Total harvest	237		109		91		78		0.0	
Cumulative harvest plus residual at age 100		422		315		307		297		236

[a] Values are totals for the 3261 ha study area.

negligible; fire disturbed up to 50 ha per decade (Table 7). The greatest total area of fire damage occurred under the even-aged intensive management regime. That regime produced the greatest area of the seedling and sapling size classes that were especially susceptible to fire damage. The least fire damage occurred under the no harvest regime. The mature forests that dominate under that regime are resistant to damage from the simulated low severity fires. Wind damage, however, was greatest under the no harvest regime and least under the intensive even-aged harvest regime.

4. Discussion

The images of the final forest size class distribution under the five different disturbance regimes visually illustrate the long-term consequences of the management alternatives (Fig. 2). However, it is the ability to quantitatively analyze the patterns displayed on the maps that makes it possible to link the visual display of size classes to factors that are relevant to humans and to wildlife. For example, the uneven-aged management regime produced seven times as much edge habitat as the no harvest regime, but only 13% as much core area. The other harvest regimes varied among these extremes and provided a range of alternative forest structures across the landscape. The best management regime for a landscape will depend on the desired future condition of the landscape and the desired products or values.

For simplicity, we concentrated on the presentation of the landscapes at the end of 100 years of simulation. However, because of fire and harvest events, the simulated landscape conditions constantly change over the course of a century. With the exception of the intensive even-aged harvest regime, which maintained a relatively constant proportion of area by size class after 60 years of simulation, the forest area by size class changed throughout the entire simulation period (Fig. 3). We could, in fact, produce images and statistics comparable to Fig. 3 and Tables 3 and 4 for each decade of the simulation. Although it becomes cumbersome here to report all statistics by decade, forest managers would certainly find many of these temporal trends of interest.

The uneven-aged, the long rotation even-aged, and the mixed harvest regimes each cut $\approx 5\%$ of the forest area each decade. The corresponding forest area by size class and decade of simulation is similar for all three of these harvest regimes (Fig.

Table 7
Mean area (ha/decade) disturbed by fire, wind, and harvest under five alternative harvest regimes

Harvest regime	Mean fire damage	Mean wind damage	Mean harvest
Even-aged intensive	50	0.1	329
Even-aged long rotation	47	0.2	150
Mixed	36	0.2	132
Uneven-aged	35	0.3	119
No harvest	27	0.4	0

3). However, the spatial distribution of forest size classes is vastly different among those three alternatives (Fig. 2, Table 3). Assumptions about the suitability of these alternative forest size and age structures for meeting wildlife habitat needs, aesthetic goals, forest biodiversity goals, efficient scheduling or forest operations, timber production and other forest values will help further distinguish these three alternatives.

The even-aged intensive harvest regime produced more than twice as much harvest volume (board ft or cubic m measure) as any other alternative (Table 5). The combined standing volume at the end of the simulation and the cumulative harvest over the simulation period was also greatest for the even-aged intensive harvest regime. At 47.2 million board feet, the total volume for the even-aged intensive harvest regime was 27% greater that the regime with the next highest volume production and 77% higher than the standing volume under the no-harvest regime. For any given harvest regime the harvested volume varied only slightly from one decade to the next. The residual standing volume increased over the simulation period for every regime except the even-aged intensive harvest. Under that regime the standing volume on the landscape fell an estimated 0.8 million board feet or 12 000 m^3 until the fifth decade where the standing volume appeared to reach an equilibrium.

The volume of down wood is an indicator of habitat quality that is often measured in old-growth forests. Down wood volume is usually greatest in very old forests (due to large trees that fall to the forest floor) or immediately following forest regeneration (due to logging residue). We estimated that the greatest mean volume of down wood over the simulation period would occur under the even-aged intensive harvest regime, but mean down wood volumes differed by no more than 5% among the harvest regimes (Table 6). Over the course of the simulation the no-harvest regime had the lowest and the highest volume of down wood. After reaching a low of 101 000 m^3 of down wood, the no harvest regime produced 209 000 m^3 by the end of the simulation, more than the other harvest regimes. Under the even-aged intensive harvest regime the majority of the down wood would occur in forest openings following harvest. In contrast, under the no harvest regime the down wood volume would occur almost exclusively beneath a mature forest overstory. Consequently, even though the mean volume of down wood over the simulation period is similar for all regimes, there are substantial differences in the type of habitat it provides and the decades when it occurs.

Differences in the landscape indices are indicative of differences in habitat quality for forest wildlife, such as neotropical migrant songbirds. For example, some migrant songbirds nest in mature forest while others nest in seedling and sapling stands (Thompson et al., 1996). Individual species will be the most abundant in landscapes that provide the greatest area of desirable habitat. Species that nest in seedling and sapling stands will be most abundant under the even-aged intensive harvest regime, and species that nest in mature forest will be most abundant under the no harvest option. Some species may be sensitive to stand size or the presence of edge; these species would do best under the no harvest or even-aged management options. Species that require habitat heterogeneity, such as ruffed grouse will be more abundant in the even-aged management, uneven-aged management, or mixed management options, but if they require large habitat patches even-aged management is superior (Thompson and Dessecker, 1997). In general, management options that provide high spatial diversity, such as the mixed management option, will result in the highest wildlife species richness unless the landscape becomes so heterogeneous that small patch sizes and associated edge habitats dominate the entire landscape.

Fire is a relatively rare event (mean fire-free interval of 300 years), but over a century of simulation up to one third of the landscape can be affected by fire. The pattern of simulated fire events is most visible in the landscape image for the no harvest regime (Fig. 2); the irregularly shaped areas that do not show up as old growth were disturbed by fire sometime during the simulation period. However, a similar pattern of fire events is also visible for the other harvest regimes. With or without timber harvest the fire and wind disturbances add diversity to the forest size and age structure.

The LANDIS model operates on age and species cohorts on a 0.09 ha site. We make a number of assumptions about the average conditions associated with a forest age class on a given site. This is a reasonable approach across the landscape, but the simulated conditions on any given site may differ greatly from what will exist on the ground in the future. Typically, estimates of forest conditions by age class have a large variance. The analyses presented here provide reasonable simulations of future landscape patterns, but the results are not suitable for site-specific planning.

5. Conclusions

The LANDIS model is a useful tool for exploring the long-term, large-scale consequences of forest management alternatives. LANDIS is not the only way to produce estimates of forest landscape change over time, but it is a method that affords considerable flexibility in exploring management alternatives. The examples we presented illustrate the complexity of long-term, large-scale forest management decisions. For individual stands, long-term changes in forest structure are easy to visualize. For landscapes comprised of numerous forest stands, the spatial and temporal patterns of forest vegetation that result from management are virtually impossible to visualize without the aid of simulation models and maps. The use of a spatially explicit model allows quantification of future landscape characteristics, including spatial and temporal distribution of forest size classes, core areas of mature forest, patch sizes, down wood volume, harvest volume, residual volume, and area of wind or fire disturbance. This model is not designed to predict the precise time and location of individual harvest events or wildfires, but it is suitable for comparing the long-term impacts of various management alternatives on landscape patterns and species composition. Among the alternatives we analyzed, the area of edge habitat, the mature forest core area, and the patch size by forest size class all varied by a factor of four or more. The cumulative harvest volumes and standing volumes at the end of the rotation varied by 21 and 13 million board feet, respectively. This model provides a quantitative framework for simultaneously exploring multiple factors associated with management decisions. The quantitative framework and the digital maps produced by the model also provide the basis for subsequent analysis of other forest and landscape characteristics.

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